News Release
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"SPOOKY PHOTONS" MAY BREAK MINIATURIZATION BARRIER FOR COMPUTERS
"Entangled" Light Can Potentially Create Smaller Circuit Patterns

Pasadena, CA (September 21, 2000) -- Every year, faster and faster computers become available. The upcoming holiday season will be no exception, with some chip speeds already being advertised in terms of gigahertz, a thousand times faster than the more familiar yardstick of megahertz. We take for granted Moore's law, the idea that computers double their speed every 18 months or so. Will this ever end?

Many experts believe the end is in sight. At some point, traditional manufacturing procedures will hit a wall on the road to faster chips. But now, physicists may have found a way to help researchers go past this dead end. In a paper to be published in the 25 September issue of the journal Physical Review Letters, researchers show that a special kind of light may eventually enable manufacturers to continue miniaturizing--and thereby speeding up--computer chips and other electronic devices well beyond what traditional techniques allow. Yet, their technique would still retain the same basic manufacturing approach, known as lithography, which uses light to sculpt the components of computer chips.

TINY TRANSISTORS
A computer chip is basically a grid of on-off switches connected to each other. A state-of-the-art chip contains millions of these switches, known as transistors. Electrical current flows through these switches in order to perform the calculations needed to crunch numbers in spreadsheets, write letters on wordprocessors, and zap aliens in computer games. How do manufacturers design faster chips? Generally, they keep shrinking the transistors to smaller and smaller sizes--allowing chipmakers to crowd together more transistors in a tinier area. This in turn means that electric current travels smaller distances through the transistors--resulting in faster processing speeds.

Currently, state-of-the-art computer chips have transistors with dimensions between roughly 180 and 220 nanometers (nm)--only about 2000 atoms wide, or about 400 times narrower than the width of a human hair. Traditional computers as we know them can function with chips having dimensions as small as 25 nm--about 250 atoms wide, or about 3000 times narrower than a human hair width. At that point, bizarre effects of the subatomic world come in, messing up the calculations of traditional computers.

But researchers have become worried that we won't even be able to reach this 25 nm limit. What is the problem?

THE LIMITS OF LITHOGRAPHY
The roadblock comes at one of the earliest steps of chip manufacture. In lithography, one first shines light on a photosensitive material to create a stencil-like "mask." Placing this mask over a block of material such as silicon, manufacturers can carve or "etch" the components that make up transistors and other electronic devices. However, chipmakers can only endow transistors and devices with dimensions as small as those on the mask. The roughly 180-220 nm features on state-of-the-art chips originate from similar dimensions on the mask.

LIGHT DICTATES THE DIMENSIONS

What determines the dimensions on lithographic masks is the behavior of light. A light beam can be visualized as a rippling wave with crests and valleys. The distance between successive crests is called the wavelength. Like a water wave passing between two rocks, a light wave can split up. Just as it happens for water continuing beyond the rocks, the waves can later recombine. In the process of recombining, it can create wave patterns smaller than its very own wavelength.

But a central principle of optics--known as the "Rayleigh criterion"--says that a light wave can't make patterns with features smaller than half its wavelength. In fact, the Rayleigh criterion says that 248-nm-wavelength "deep ultraviolet" light--currently used to make the chips with the approximately 180-220 nm dimensions--can't create chips with features smaller than 124 nm. Smaller features are possible by using shorter-wavelength light, but such light gets more and more difficult to produce as you go to shorter wavelengths.

QUANTUM PHYSICS REWRITES THE RULES

In new research by Jonathan Dowling of JPL/Caltech and his colleagues, physicists illustrate that the Rayleigh criterion is mainly a limit of classical, pre-20th century physics--and not of the "quantum" physics discovered and explored since the 20th century. This research--still a theoretical proposal at this stage--is made by a team of physicists at the Jet Propulsion Laboratory, the California Institute of Technology, and the University of Wales, Bangor. Their proposal is based on earlier insights and results by physicists at many other institutions, including UCLA, the University of Rochester, Boston University, and the University of Maryland, and the Federal University of Minas Gerais in Brazil.

Dowling and his colleagues show that existing sources of light can potentially make chips with dimensions that are much smaller fractions of the wavelength than classical physics allows. In their scenario, 248-nm light could make features as tiny as 62 nm--a fourth of the wavelength--or potentially much smaller--through a quantum physics process known as "entanglement."

ENTANGLEMENT

To understand entanglement, it's useful to temporarily visualize a light beam not as a wave, but as a stream of particles called photons. In this "particle" picture of light, photons are usually unaffected by one another--each photon normally behaves independently of its neighbors. But sometimes two or more photons can become interlinked or "entangled"--whereby the properties of one photon are dependent upon the properties of its partners. As physicists like to say, entangled photons are "correlated" with each other. Albert Einstein called this process "spooky action at a distance" because the particles can seem to influence each other instantly, even if they become separated by the distance of a galaxy or more! In the laboratory, entangled photons can be produced by passing a light beam through a special crystal.

A QUANTUM LEAP FOR LITHOGRAPHY

The entangled photons come into play in the researchers' proposal for "quantum interferometric optical lithography," an exotic version of lithography that takes advantage of the unique properties of the quantum world. In their proposal, two entangled photons enter a setup with a pair of paths. The photons travel as a single unit. However, the setup is designed so that it is impossible to determine if the two-photon unit takes the first path or the second path. This very property makes the photon pair behave once again as a single rippling wave. This wave splits up to travel both paths. Eventually, the two parts of the wave are made to recombine on a surface. Because the two photons constituting the light wave are entangled with each other, and therefore are correlated in a special way, they create patterns equivalent to those made by a single photon with half the wavelength.

Therefore, an entangled pair of photons each with 500 nm wavelength would act as a single photon with 250 nm--allowing researchers to write 125 nm patterns on a side, two times smaller than the Rayleigh criterion allows for a single "classical" photon with a 500-nm wavelength. Such an entangled pair could write circuit patterns with four times smaller area, since the surface of a mask has two dimensions, length and width, and there is a twofold improvement on each side. Preparing a trio of entangled photons--a difficult task--and sending them through the device would create even better results: they would act as a single photon with a third of the wavelength, enabling patterns with nine-fold smaller area on a chip. Entangling four entangled photons--more difficult yet--could produce patterns with a 16-fold smaller area, and so on.

CHALLENGES LIE AHEAD

To realize this proposal, researchers need to surmount numerous technical challenges. Towards these ends, scientists are developing "two-photon resists," materials designed to absorb photon pairs arriving simultaneously. But, for example, they have yet to develop the special materials required to generate entangled photons at short wavelengths. Still, physicists are already working on demonstrating simple versions of this proposal. One of them is Yanhua Shih, a professor of physics at the University of Maryland in Baltimore County.

"My laboratory is working on this new idea of optical lithography experimentally," says Shih. "Jon Dowling and his co-workers did not only propose a new way of conducting lithography in this paper," according to Shih, who has done related experiments on entanglement. "The fundamental idea is far more important, in my opinion. It is a great idea to utilize this very important physics to the application of lithography."

"I am impressed at the very clever application of some very fundamental features of the quantum mechanics of the electromagnetic field," comments Carlos Stroud, a professor of optics and physics at the University of Rochester. "That said, there would appear to be rather substantial engineering problems before we get super-dense computer chips. These engineering problems may be a lot tougher than the quantum problem. Still, it clearly demonstrates the advances that are available when technology really is able to take advantage of quantum coherence. It is a nice step in that direction."

FUTURE POSSIBILITIES

The new proposal opens the possibility of using light at existing wavelengths to manufacture computer chips smaller than 25 nm, the size limit below which classical computer designs begin to fail. "In classical computing, these quantum effects are viewed as bad," says Dowling of JPL/Caltech. "However, we embrace these quantum effects and exploit them," he says. Such effects can lead to interesting new electronic devices taking advantage of processes in the quantum realm.

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SOURCE

"Quantum Interferometric Optical Lithography: Exploiting Entanglement to Beat the Diffraction Limit," Agedi N. Boto, Pieter Kok, Daniel S. Abrams, Samuel L. Braunstein, Colin P. Williams and Jonathan P. Dowling, Physical Review Letters, 25 September 2000 (available to journalists upon request).

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